CONDUCTIVE WHITE THERMAL CONTROL PAINT FOR SPACECRAFT - PART 2

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ABSTRACT

Thermal control paints were evaluated for use as electrically conductive white thermal control coatings on the Saturn-bound NASA/Jet Propulsion Laboratory Cassini spacecraft. The primary candidate paints evaluated were PCBZ, NS43G, HINCOM, and NS43G/HINCOM. HINCOM is an aluminum oxide doped zinc oxide pigment paint developed at the Jet Propulsion Laboratory in collaboration with J. Cordaro. NS43G/HINCOM is a paint which is prepared using a 50%/50% by weight mixture of HINCOM and NS43G as the pigment. Electrical conductivity, solar absorptance and infrared emittance, and resistance to the radiation environment of the Cassini mission were evaluated. In addition, adhesion to aluminum, graphite/epoxy composite and KAPTON substrates, and thermal cycling and thermal shock resistance were evaluated. The NS43G/HINCOM paint exhibited excellent optical properties, solar absorptance of 0.20 and infrared emittance of 0.91, and electrical conductivity met mission requirements. On the basis of completing previous radiation resistance studies, it was possible to predict that NS43G/HINCOM coatings have excellent environmental resistance to both ultraviolet and particle radiation, This combination of excellent optical properties combined with high electrical conductivity and environmental resistance represents a major advance in electrically conductive white thermal coating technology. NS43G/HINCOM and HINCOM are the primary candidate thermal control coatings for use on the Cassini spacecraft,

KEY WORDS: Electrically Conductive, White Thermal Control Paints

1. INTRODUCTION

The NASA/Jet Propulsion Laboratory Cassini project is a major interplanetary exploration effort to study Saturn, its moons and atmosphere. The Cassini spacecraft is scheduled for launch in 1997. Its seven year voyage to Saturn will include several flybys of Earth and Venus to achieve gravity assisted acceleration. Upon arrival at Saturn, a four year mission will be conducted, with fifty orbits and many satellite encounters. Detailed studies of Saturn's atmosphere, rings and magnetosphere will be conducted, The Huygens atmospheric entry probe provided by the European Space Agency will be used to study Titan, Saturn's principal moon.

The principal area of application for conductive thermal control coatings on the Cassini spacecraft is the four meter diameter High Gain Antenna (HGA) system, The HGA system, which is being manufactured by Alenia Spazio of Italy under the sponsorship of Agenzia Spaziale Italiana (ASI), has a four meter diameter main reflector fabricated from epoxy matrix carbon fiber composites in a sandwich construction with aluminum core and a Frequency Selective Subreflector (FSS) fabricated using KEVLAR core and KEVLAR/epoxy composites with a KAPTON film over a copper grid. A much smaller Low Gain Antenna (LGA-1) is mounted on top of the main reflector. An effective thermal control coating is of critical importance because extremes of temperature will be encountered as the spacecraft will approach within 0.61 astronomical units (AU) of the sun during Venus flybys and will be as far as 10 AU from the sun while orbiting Saturn. Electrical conductivity of the HGA thermal control coating is necessary to prevent electrical discharge damage to the onboard electronic equipment and to avoid electromagnetic interference with onboard field and particle detectors. Because of the long duration of the Cassini mission, environmental resistance, as well as electrical conductivity and good thermal control properties, is important.

Based on mission requirements, performance goals and evaluation criteria were established for candidate conductive thermal control coatings. The coating should be capable of being applied in a smooth, uniform coat to a large object such as the High Gain Antenna and should exhibit good adhesion to both metallic and non-metallic substrates to permit usage throughout the Cassini spacecraft. The coating should be capable of withstanding thermal cycling between 180 "C and -180 "C and should also be capable of withstanding ultraviolet exposure of 19,000 equivalent sun hours (ESH). The electrostatic discharge requirement which has been established for the mission is that charge buildup should not exceed 10 volts when the coating has been subjected to a bombardment of 10 keV electrons at a current density of 0.5 nA/cm^2. Effective thermal control requires good optical properties, a low solar absorptance and a high infrared emittance. Absorptance values of 0.20 or less and emittance values of 0,90 or greater were considered to be highly desirable. Low specularity, less than one percent, was also considered highly desirable to minimize heating of the Frequency Selective Subreflector (FSS) by radiation reflecting from the HGA.

To meet the thermal control coating needs of the HGA system in particular, and the Cassini spacecraft in general, a collaborative research and development effort was established involving the Jet Propulsion Laboratory (JPL), Alenia Spazio, the manufacturer of the HGA, and Professor James Cordaro at Michigan Technological University.

Three candidate systems, PCBZ, NS43G, and HINCOM, a new aluminum oxide doped zinc oxide pigmented paint developed at the Jet Propulsion Laboratory in collaboration with Dr. James Cordaro of Michigan Technological University, had been evaluated previously. None of the three candidate systems was entirely satisfactory. NS43G offered excellent environmental durability, and electrical conductivity met mission requirements, but these benefits were offset in part by the high absorptance, beginning of life value of 0.29. PCBZ had good beginning of life optical properties and the electrical conductivity came close to meeting mission requirements. Environmental testing, however, indicated that radiation exposure resulted in a substantial increase in absorptance. HINCOM provided excellent optical properties and environmental resistance, however, the electrical charging was substantially above mission requirements, -109 volts vs. a maximum of 10 volts allowed.

It was decided to carry out additional studies on the three candidate systems. In addition, another candidate system, HINCOM/NS43G, a paint prepared using a pigment which consisted of a 50%/50% by weight mixture of HINCOM and NS43G would be evaluated. Previous studies, such radiation resistance and electrical conductivity would be completed, and additional work would be performed in areas such as optimization of coating adhesion to a variety of substrates. The results of these studies would form the basis for selection of electrically conductive white thermal control coatings to be used on the Cassini spacecraft.

2. EXPERIMENTAL

2.1 Paint Preparation

2.1.1 PCBZ Paint preparation and application procedures were defined according (o the directions provided by M. A. P., the paint supplier. For PS-Primer, the primer recommended by M.A.P. for use with PCBZ on composite substrates, the following formulation was used: PS-Base, 83 parts by weight; PS-Hardener. 17 parts by weight; dilution with PS-Thinner, 25 percent by weight. Viscosity was checked to verify that it was within the allowable range, 14 to 18 seconds measured an Afnor Cup No. 4. For the PCBZ Basecoat, the PCBZ-Base was diluted with PCBZ-Thinner using 15 percent by weight as the dilution ration. Viscosity was checked to verify that it was in the allowable range, 20 to 30 seconds measured by an Afnor Cup No. 4. PCBZ-Topcoat was diluted with PCBZ thinner, using 42 percent by weight as the dilution ratio. Viscosity was checked to verify that it was in the allowable range, 33 to 35 seconds measured by an Afnor Cup No. 2.5.

2.1.2 ***NS43G*** NS43G was obtained from Space Craft Coatings, inc. of Gambrils, Maryland. NS43G coatings were prepared using a 3:1 ratio of pigment to binder. The binder was KASIL 2135, a potassium silicate compound supplied by the PQ corporation, For preparation of a coating, the following, formulation was used in the typical amounts indicated:

NS43G pigment	130 grams
KASIL2135 binder	41.8 grams
distilled water	15.6 grams

The pigment, binder and distilled water were thoroughly mixed in a glass beaker of suitable size and the resulting mixture transferred to a ball milling jar and ball milled for at least 8 hours.

2.1.3 HINCOM HINCOM pigment was supplied by Union Miniere. HINCOM coatings were prepared using a 3:1 ratio of pigment to binder. The binder wasKASIL2135. For preparation of a coating, the following formulation was used in the typical amounts indicated:

HINCOM pigment	130 grams
KASIL2135 binder	41.8 grams
distilled water	50 grams

The pigment, binder and distilled water were thoroughly mixed in a glass beaker of suitable size and the resulting mixture transferred to either a glass or ceramic ball milling jar. 10 grams of distilled water were used to wash the residue from the beaker to the ball milling jar. The mixture was ball milled for a minimum of 6 hours and a maximum of ten hours. During the ball milling process, the mixture was checked and additional distilled water, typically 10 grams, was added as needed. After completion of ball milling, the mixed paint was transferred to the spray gun cup using a 300 micron filter,

2.1.4 NS43G /HINCOM NS43G/HINCOM coatings were prepared in the same manner that HINCOM coatings were prepared. KASIL2135 was the binder, and a 3:1 pigment to binder ratio was used. For preparation of a coating, the following formulation was used in the typical amounts indicated:

HINCOM pigment	65 grams
NS43G pigment	65 grams
KASIL2135 binder	41.8 grams
distilled water	33 grams

The pigment, binder and distilled water were thoroughly mixed in a glass beaker of suitable size and the resulting mixture transferred to either a glass or ceramic ball milling jar. 10 grams of distilled water were used to wash the residue from the beaker to the ball milling jar. The mixture was ball milled for a minimum of 6 hours and a maximum of ten hours, During the ball milling process, the mixture. was checked and additional distilled water, typically 10 grams, was added as needed. After completion of ball milling, the mixed paint was transferred to the spray gun cup using a 300 micron filter.

In preparing HINCOM and NS43G/HINCOM coatings, we found that it was difficult to precisely define the amount of distilled water which was required, Variations of several grams occurred as we attempted to optimize handling characteristics. What constitutes optimum handling characteristics will be based, at least in part, on the paint spraying apparatus being used as well as the size, geometry and application of the article being painted. The above formulations for HINCOM and NS43G/HINCOM will, however, serve as useful guidelines, Detailed materials and processes specifications are being prepared for the usc of HINCOM and NS43G/HINCOM coatings on the Cassini spacecraft.

2.2 Surface Preparation of Substrates and Paint Application Procedures

Aluminum, graphite/epoxy composite sandwich panels, KEVLAR/epoxy, and KAPTON coated KEVLAR/epoxy composite sandwich panels were used for adhesion substrates. The aluminum was 6061 -T6. The graphite/epoxy composite sandwich panels were prepared from unidirectional DIALED/934 prepreg tape and aluminum core, The KAPTON coated composite sandwich panels consisted of facesheets composed of KEVLAR/F- 161 facesheets with a KAPTON film over a copper grid at the surface and a KEVLAR core.

PCBZ coated aluminum substrate specimens were prepared at JPL for use in the radiation resistance and specularity studies and for some electrical conductivity studies. Prior to application of the coatings, the aluminum substrates were scoured with a Scotch Brite pad dipped in a paste mixture of Alconox detergent powder, Institutional Grade Ajax scouring cleanser, and water. The substrates were rinsed thoroughly, first with tap water and then with deionized water. The substrates were immersed in deionized water until all of the substrates had been cleaned The substrates were removed from the water, one at a time, and then dried using a current of oil-free, dry nitrogen gas.

Before applying PCBZ coatings, the aluminum substrates were then wiped with 1,1,1 trichloroethane and wiped or rinsed with acetone. The substrates were then rub primed with the PCBZ base paint. One mist coat and one box coat, two crossed coats, of the base paint was then sprayed on. The base coat was then allowed to dry for up to one hour and then one or two box coats of the PCBZ topcoat paint were applied. The manufacturer's directions stipulated that no more than three minutes should elapse prior to application of the topcoat, but it was found that waiting as long as one hour still produced acceptable adhesion. The painted substrates were then allowed to dry for 5 days at ambient temperature with the relative humidity maintained at greater than 40%.

PCBZ specimens on composite substrates were prepared at Alenia Spazio. The composite surface was first abraded with 220 grit sandpaper, rinsed with 1,1,1 trichloroethane, and then rinsed or wiped, with acetone and ethyl alcohol. As recommended by M.A.P. for composite substrates, PS-Primer was then applied. One and one half cross coats of PS-Primer (25 to 30 microns total thickness) were applied and allowed to dry for a minimum of 24 hours and a maximum of 48 hours. Afterwards, two cross coats of PCBZ Basecoat (40 to 50 microns total thickness) were applied. Within 15 minutes, one and one half cross coats of PCBZ-Topcoat (30 to 40 microns total thickness) were applied. The painted samples were allowed to dry for 5 days at room temperature and a relative humidity of approximately 50%.

The preparation procedures for applying NS43G and HINCOM coatings to aluminum substrates were similar to those used for PCBZ except that wiping or rinsing with 1,1,1 trichloroethane was not performed, no basecoat was applied and rub priming was done with the paint itself. A box coat of the paint was then sprayed on and the painted substrates were allowed to cure for 14 days at ambient temperature with the relative humidity maintained between 50% and 80%, with 65% to 80% being the preferred range,

To prepare NS43G, HINCOM and HINCOM/NS43G specimens on graphite/epoxy composite substrates, the composite surface was wiped with acetone and then ethanol, abraded with 220 grit sandpaper, and then wiped with acetone. and then ethyl alcohol. A similar approach was used with KAPTON coated composite substrates except that abrasion was performed using ultrafine Scotch Brite. These pretreatment procedures were followed by the use of additional surface priming procedures, such as the application of silane coupling agents or epoxy or silicone primers. Both the graphite/epoxy and KAPTON coated composite substrates 'were then painted using the paint application and curing procedures described above. Details and results of the adhesion study performed using these coated substrates arc presented in Section 3.4.

2.3 Testing Procedure

2.3.1 ***Optical Properties*** Optical properties, solar absorptance and infrared emittance, were measured both at Alenia Spazio and at JPL using Gier-Dunkle reflectometers. Specularity measurements were performed by Surface Optics, Inc. of San Diego.

2.3.2 ***Adhesion*** Adhesion was measured using ASTM D3359. Method A was used at JPL, and Method B was used at Alenia Spazio. This procedure involves making cuts in the surface of the coated substrate, placing a strip of taped over the cuts, peeling off the tape and evaluating the amount and pattern of any removal of the coating. Method A involves making a single intersecting x-cut in the substrate, while Method B involves making multiple intersecting cuts, resulting in a rectangular cross hatch pattern, The rating scale extends from OA or OB (very poor adhesion) to 5A or 5B,(excellent adhesion). For the purposes of this study, an adhesion rating of at least 3A or 3B was considered acceptable.

2.3.3 ***Electrical Conductivity*** Electrical conductivity was evaluated on the basis of a coating being able to meet the Cassini project requirement of charging to no more than 10 volts when subjected to a 10 keV electron bombardment at a current density of 0.S nA/cm^2.

The electrical conductivity measurement methodology has been described in detail previously[1]. Coated samples and a biased calibration strip were placed in a vacuum chamber, which was then evacuated to a pressure of 2x 10^{-3} Pa or less. Samples were heated to 130 °C for a minimum of 48 hours. After bombardment with 1,3,5,7, an 10 keV electron streams at a current density of 0.5 nA/cm^2, non-contact charging measurements were made using a Trek Probe moved along the y-direction of each sample. Charging measurements were then continued for at least 24 hours. After elevated temperature measurements were performed, the samples were then cooled to ambient while vacuum was maintained. Liquid nitrogen was then used to cool the samples to temperatures as low as -180 'C, and sub-ambient charging measurements were then performed in a similar manner. Performing charging measurements under vacuum with an in-situ drying step was found to be necessary to eliminate the effects of adsorbed moisture and achieve reliable results.

2.3.4 ***Radiation Resistance*** Previously reported studies[1] on the resistance of candidate coatings to electron, proton and ultraviolet exposure were completed. These exposure tests were performed at the Space Environmental Test Facility of Lockheed Missiles and Space Company in Sunnyvale, California.

Aluminum discs 3.17 cm in diameter were coated with PCBZ, NS43G and HINCOM using the standard sample preparation procedures described above and then submitted to Lockheed. A total of 8 coating samples were mounted on a target plate with a front surface aluminized mirror used for test calibration/contamination monitoring mounted in the center. The target plate was then placed in the vacuum test chamber. [Ultraviolet exposure was provided with 4200 watt xenon lamps of one sun intensity. Vacuum ultraviolet exposure was provided with a deuterium lamp of 1 to 2 sun intensity, based on intensity at Lyman Alpha, 1216 Å. Radiation particle fluxes were in the range of 10^{13} to 10^{14} electrons or protons/cm^2/sec. Flux durations of 1000 seconds were used. Emittance was measured ex-situ with a Gier-Dunkle heated cavity reflectometer. Absorptance was measured ex-situ with a Cary 17D spectrophotometer and measured in-situ with a Perkin Elmer Lambda 9 spectrophotometer.

2.3.S ***Thermal Cycling/Thermal Shock*** Thermal cycling and thermal shock resistance studies were conducted at Alenia Spazio. Resistance to thermal cycling was determined by exposing samples to thermal cycling for a total of 27 times between -180 °C and +180 'C. There was a 60 minute pause at each temperature extreme, and the rate of temperature change was 2 °C pcr minute. Thermal shock tests were performed **by** cycling specimens between 190 °C **and -70** °C for a total often times. There was a 1 S minute pause at each temperature extreme. Specimens were rapidly shuttled mechanically between the two sections of an environmental testing chamber that were maintained at the two temperature extremes, Overall rate of temperat ure change was approximately 11 'C to 12 °C per minute.

2.3.6 ***Vacuum Stability and Outgassing*** Vacuum outgassing requirements established for the Cassini project are that the total mass loss (TML) shall not exceed 1.()% and vacuum condensable material (VCM) shall not exceed 0.1 %. Each of the candidate coatings was evaluated for vacuum stability and outgassing using thermal vacuum drying steps which varied somewhat with the material being tested.

3. RESULTS AND DISCUSSION

3.1 **HINCOM/NS43G** The optical properties, electrical conductivity and adhesion of HINCOM/NS43G coating on aluminum substrates were evaluated. The following results were obtained:

absorptance	0.20
emittance	0.91
electrical conductivity	-10 volts charging at 10 keV and 0.5 nA/cm^2 current density
adhesion to aluminum '	3A/4A

The absorptance was substantial] y lower than that of NS43G, the electrical conductivity met Cassini project goals, and the adhesion to aluminum substrates was acceptable. On the basis of these favorable preliminary results, it was decided to include HINCOM/NS43G coating in further coatings evaluation studies.

3.2 RADIATION RESISTANCE A summary of the complete results of the radiation tests performed at Lockheed is presented in Table 1. 'Tie total exposure to electron and proton radiation was twice that estimated for the Cassini mission. The total ultraviolet radiation exposure of 2450 hours was significantly less than the Cassini project requirement of 19,000 hours. We felt, however, that an exposure of 2450 hours would be of sufficient duration to reveal significant trends in the degradation of optical properties.

The results indicate that both NS43G and HINCOM exhibit exceptional resistance to ultraviolet radiation. While there was some effect from exposure to electron and proton radiation, the optical property degradation was regarded as relatively minor and of a magnitude consistent with use of the coatings on the Cassini spacecraft. Unlike the HINCOM and NS43G coatings, which use silicate binders, the PCBZ uses a silicone binder. As expected, the PCBZ exhibited a greater degree of degradation of optical properties, both from ultraviolet radiation exposure and from exposure to electron and proton radiation,

3.3 **SPECULARITY** It was considered very important that the coating exhibit a low specularity. A high degree of specular reflectance for the coating of the main reflector would result in the reflection of too much incident solar radiation onto the rear of the Frequency Selective Subreflector (FSS), resulting in too high a temperature for the FSS.

To evaluate the specularity of the candidate coatings, samples of PCBZ, NS43G, and HINCOM on aluminum substrates were prepared and submitted to Surface Optics Corporation of San Diego. Bidirectional reflectance data for each of the samples were obtained and analyzed. These data indicated that all three coatings exhibited very low specularity, typically below 0.5%. This low degree of specularity was considered to be consistent with the use of these coatings on the HGA. While the specularity of N43G HINCOM was not determined, it was assumed on the basis of its similarity to NS43G and H NCOM that the specularity of NS43G/HINCOM would also be satisfactorily small.

3.4 ADHESION It was considered critical to demonstrate adhesion to substrates whose surfaces duplicated the. actual articles on the Cassini spacecraft to which the coatings would be applied. Our earlier study had indicated that adhesion to aluminum substrates was satisfactory. It had also been demonstrated that adequate adhesion of NS43G and PCBZ to composite substrates could be achieved under ambient conditions. We expanded upon our earlier work to include HINCOM and NS43G/HINCOM coatings and KAPTON coated composite substrates. We also evaluated the effects of thermal shock and thermal cycling on coating adhesion.

A preliminary study was conducted using NS43G, HINCOM, and PCBZ coatings on graphite/epoxy, KAPTON, and aluminum substrates. Per the recommendation of M, A. P., PCBZ coatings on graphite/epoxy and substrates were applied using PS-primer, followed by applying the basecoat and topcoat according to the standard procedures recommended by M.A.P. For the NS43G and HINCOM, the pretreatment consisted of spraying on a 1% by weight solution of 2-6040 coupling agent in anhydrous methanol, allowing it to dry then applying one or more box coats of either HINCOM or NS43G. Adhesion tests were then performed, both before and after thermal cycling.

The results of this preliminary study are presented in Table 2. PCBZ exhibited excellent adhesion, before and after thermal cycling. Both NS43G and HINCOM showed good adhesion to graphite/epoxy substrates before thermal cycling and very poor adhesion after thermal cycling. Neither NS43G nor HINCOM coatings showed good adhesion to KAPTON coated substrates before thermal cycling. Therefore, the specimens were not thermal cycled. In addition to adhesion, optical properties were measured both before and after thermal cycling. The results in Table 2 indicate no significant changes in the absorptance and emittance of either HINCOM or NS43G coatings as a result of thermal cycling, and only small changes in the absorptance and emittance of PCBZ after thermal cycling.

Based upon the results of our preliminary study, we decided to pursue other surface pretreatment procedures, using HINCOM and NS43G/HINCOM coatings. Neither PCBZ,NS43G, nor NS43G/HINCOM were evaluated on KAPTON substrates because the high electrical conductivity of these systems would have resulted in unacceptably high radiofrequency losses if they were used as coatings for the FSS. HINCOM and NS43G/HINCOM offered substantially better optical properties than NS43G. Although HINCOM did not meet the charging potential requirement, its use on the FSS and on the front surface of the main reflector of the HGA, ,where the instrumentation would be effectively shielded from high charge buildup was considered to be acceptable.

The surface pretreatment procedures used included using 2-6040, DC- 1200 and DC- 1205 silane coupling agents, either sprayed on from dilute solutions in alcohol or rub primed on as a mixture with the paint, For KAPTON substrates, etching of the substrate surfaces with concentrated sodium hydroxide was tried, as well as the use of silicone and epoxy primers. Prior to use of any of these surface pretreatment procedures, both the graphite/epoxy and KAPTON substrates were cleaned with acetone and ethanol., abraded and then recleaned with acetone and ethanol according to the procedures described above.

The results of this adhesion study are summarized in Table 3. Good adhesion of HINCOM coatings to KAPTON substrates can be achieved by rub priming with either a HINCOM/Z-6040 mixture or a HINCOM/A-1 100 mixture prior to application of the HINCOM paint. Each of these rub prime mixtures consisted of 1 part by weight coupling agent and 6 part by weight HINCOM paint, Rub priming with the HINCOIVUA-1100 mixture appears to provide better results. Poor adhesion of HINCOM coatings to graphite/epoxy substrates was achieved rub priming with the HINCOM/Z-6040 mixture prior to application of HINCOM. Excellent adhesion of NS43G/HINCOM coatings to graphite epoxy substrates was obtained by rub priming with a mixture consisting of 1 part by weight 2-6040 and 6 parts by weight NS43G/HINCOM paint prior to application of the NS43G/HINCOM paint, These successful experiments have allowed us to establish HINCOM paint as the primary candidate thermal control coating for the FSS and NS43G/HINCOM as the primary candidate thermal control coating for the main reflector.

In addition to the work summarized in Table 3, we tried a number of unsuccessful approaches, Etching of KAPTON surfaces with concentrate sodium hydroxide thixotropic pastes was unsuccessful, as was the use of epoxy and silicone primers. We were also unable to achieve adequate adhesion of NS43G/HINCOM to an aluminized KAPTON surface.

3.5 Effects of Refiring Temperature and Pigment-to-Binder Ratio on the Electrical Conductivity of HINCOM Coatings HINCOM coatings did not have the electrical conductivity sufficient to meet Cassini project. We decided to see if refiring the HINCOM pigment at higher temperatures and altering the pigment-to-binder ratio would improve the electrical conductivity of HINCOM coatings, HINCOM pigment as received from Union Miniere has been fired to 900 °C. Two small batches of the as-received HINCOM were refired at 1050 "C for 15 minutes. The refired pigment was used to manufacture a coating with a 5.5:1 pigment to binder ratio and a coating with a 3:1 pigment to binder to ratio. A control sample was prepared using non-refired pigment and a 3:1 pigment binder. Absorptance, emittance and charging potential for each of the samples was determined using the above described test methods. The results are as shown in Table 4.

From the data in Table 4, it is evident that refiring of the pigment and alteration of the pigment-to-binder ratio can significantly improve the conductivity of HINCOM coatings, although at the cost of a small increase in absorptance. Further experiments involving additional variations of refiring temperature and pigment-to-binder ratio might result in additional improvements in electrical conductivity while maintaining good optical properties.

3.6 Effect of Topcoat Thickness on the Conductivity and Optical Properties of PCBZ Coatings. Because PCBZ derives its electrical conductivity from a dark, highly conductive basecoat and its good optical properties from a white topcoat, the thickness of the topcoat can have a significant effect on the balance of electrical properties and optical properties. Electrostatic discharge and optical property measurements were performed on a PCBZ coated aluminum sample which had two crossed coats of topcoat, a similar sample with one crossed coat of topcoat, and a PCBZ coated sample of graphite/epoxy composite that had one and one half crossed coats of topcoat (40 microns). Table 5 summarizes the data relating optical properties and topcoat thickness. The data in Table 5 show that if the topcoat of PCBZ is thin enough, PCBZ coatings can be made to satisfy the Cassini electrostatic discharge requirement, although at a sacrifice of optical properties.

3.7 Vacuum Stability and Outgassing After a 16 hour bakeout at 120 "C and 10- I Pa, it was found that PCBZ met Cassini project requirements. Total Mass Loss (TML) was 0.23%, Vacuum Condensable Material (VCM) was 0.08%, and Water Vapor Recovered (WVR) was 0.05%, We had reported previously that NS43G did satisfy Cassini project requirements with a TML of 1.0% and a VCM of 0.05%. We had also reported earlier[1] that HINCOM did not meet Cassini requirements. Vacuum stability and outgassing data for NS43G/HINCOM coatings has not yet been performed. After a 24 hour bakeout at 100 "C and 0.1 Pa, the TML was 1.60%, the VCM was 0.02%, and the WVR was 1.40%.We anticipate, however, that with a sufficiently rigorous drying step, TML and VCM for HINCOM coatings will meet requirements. Vacuum stability and outgassing tests have not yet been performed on NS43G/HINCOM, but we anticipate that the situation will be very similar to that of HINCOM.

4. CONCLUSIONS

A summary of the electrical conductivity, optical property, and adhesion data obtained for all four candidate systems is presented in Table 6, along with our estimates for the end-of life optical properties. These estimates are based upon the data from the radiation resistance studies conducted at Lockheed. Although the electron and proton radiation doses were twice those expected during the Cassini mission, the ultraviolet radiation exposure of 2450 ESH was significantly below the)9,000 ESH level projected for the Cassini mission. Therefore, we tried to extrapolate ultraviolet radiation degradation to the 19,000 ESH level. Our end of life estimates also included an uncertainty factor to account for any effects not yet fully evaluated, such as the effects of high energy particle radiation. High energy particle radiation studies are currently being conducted at Lockheed, but the results were not available in time for inclusion in this paper.

HINCOM/NS43G samples were not included in the radiation resistance tests, therefore, estimates of end of life optical properties were based upon beginning of life optical property data obtained in-house and basing our estimate of end-of-life properties on the arithmetic mean of radiation resistance test results from HINCOM and from NS43G. The PCBZ data presented in Table 5 are based upon a PCBZ coated graphite/epoxy sample prepared with a thinner topcoat in order to maximize the electrical conductivity. Radiation resistance tests had been performed on PCBZ coated aluminum substrates with somewhat thicker topcoats. Estimates of end of life optical properties are based upon our in-house optical property measurements for beginning of life optical properties and using the radiation resistance test results to estimate end of life optical properties.

On the basis of the results of our studies of electrically conductive white thermal control coatings, it appears that HINCOM/NS43G paint offers the best combination of electrical conductivity, optical properties, and environmental durability. In instances where electrical conductivity is less critical and optical properties of greater importance, the use of HINCOM paints is warranted. For the Cassini spacecraft, the use of HINCOM on the FSS, an area where thermal control and good optical properties are of primary importance and electrical conductivity is relatively less important, is under consideration. For the main reflector, particularly for the back surface, very near to the spacecraft instrumentation, a different set of priorities prevails, and the use of NS43G/HINCOM is under consideration.

NS43G affords the highest electrical conductivity although the initial absorptance is relatively high, 0.29. PCBZ provides good electrical conductivity, excellent adhesion to hard-to-adhere surfaces such as KAPTON, and good initial optical properties, although absorptance does increase substantially with exposure to radiation. Substantial progress has been realized in improving the adhesion of HINCOM coatings to KAPTON coated composite substrates Similar progress has been demonstrated in improving the adhesion of HINCOM/NS43G coatings to graphite/epoxy substrates. Good adhesion of all four coatings to aluminum substrates, even after exposure of coated samples to rigorous thermal cycling and thermal shock regimes, was achieved. was achieved. Good adhesion of HINCOM/NS43G, and PCBZ coatings to graphite/epoxy composite substrates, even after exposure of coated samples to rigorous thermal cycling and thermal shock regimes was achieved. Good adhesion of HINCOM coatings to KAPTON coated KEVLAR/epoxy composite sandwich substrates and to KEVLAR/epoxy composite sandwich substrates, even after exposure to rigorous thermal shock and thermal cycling routines was also achieved.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

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TABLE 1. RESULTS OF RADIATION TEST OF WHITE PAINTS

SPECIMEN NO.	PAINT SYSTEM	ABSORPTANCE[1]								
		PRETEST/ VACUUM	120 ESH UV TOTAL[3]	275 ESH UV TOTAL	PLUS $2X10^{13}$ p+/CM² (115 KeV)	PLUS $4X10^{13}$ p+/CM² (70 KeV)	PLUS $1.6X10^{14}$ p+/CM² (30 KeV)	PLUS $8X10^{13}$ e-/CM² (30 KeV)	446 ESH UV TOTAL	821 ESH UV TOTAL
AL CONTAMIN MONITOR		.18	.18	.18	.17	.17	.18	.17	.18	.18
70	NS43G/PS-7	.24	.24	.23	.25	.25	.25	.26	.26	.25
71		.25	.24	.24				.27	.25	.25
1B	NS43G/KASIL-2135	.31	.31	.31	.31	.31	.32	.32	.32	.31
2B		.29	.29	.28				.31	.30	.30
33	HINCOM	.19	.18	.18				.20	.20	.20
34		.19	.19	.18	.19	.19	.21	.21	.20	.21
RPZ1	PCBZ (Z TOPCOATS)	.16	.18	.18	.18	.19	.22	.22	.22	.23
PR10	PCBZ (1 TOPCOAT)	.21	.22	.22	.22	.23	.26	.25	.26	.26
$BaSO_4$ STD[2]		.033/.035	.033/.031	.033/.032	.032/.035	.033/.037	.034/.023	.034/.031	.033/.038	.033/.036
Al STD		.18	.17	.17		.17/.16	.17	.17	.18	.18

NOTE: 1) All measurements with $BaSO_4$ calibration, measured in vacuum.
2) Values obtained at start/finish of sample measurement process.
3) After the 60 esh UV exposure, chamber pressure was at a max of 107 Pa for less than 20 minutes.

TABLE 1. RESULTS OF RADIATION TEST OF WHITE PAINTS (continued)

SPECIMEN NO	PAINT SYSTEM	ABSORPTANCE[1]											
		PLUS $2X10^{13}$ p^+/CM^2 (115 KeV)	PLUS $4X10^{13}$ p^+/CM^2 (70 KeV)	PLUS $1.6X10^{14}$ p^+/CM^2 (70 KeV)	PLUS $8X10^{13}$ e^-/CM^2 (25 KeV)	1357 ESH UV TOTAL	POST TEST IN AIR	14 DAYS IN AIR (VACUUM CHAMBER)	1453 ESH UV TOTAL[3]	1381 ESH UV TOTAL[3]	1.5 MONTHS IN AIR (VACUUM CHAMBER)	1934 ESH UV TOTAL[5]	2450 ESH UV TOTAL[3]
AL CONTAMIN MONITOR		.18	.18	.18	.18	.19	.18	.19	.18	.19		.19	.19
70	NS43G/PS-7	.25	.27	.27	.28	.26	.25				.25	.26	
71					.28	.26	.26				.25	.26	
1B	NS43G/KASIL-2135	.32	.32	.33	.33	.32	.31	.31	.31	.32			.32
2B					.32	.31	.30				.30	.31	
33	HINCOM				.22	.21	.21				.20	.21	
34		.21	.22	.23	.23	.22	.21	.20	.21	.22			.22
RPZ1	PCBZ (2 TOPCOATS)	.22	.23	.25	.25	.25	.20	.19	.23	.25			.25
PR10	PCBZ (1 TOPCOAT)	.26	.27	.28	.28	.29	.25	.24	.26	.28			.28
$BaSO_4$ STD[2]		.036/ .026	.033/ .035	.035/ .035	.034/ .031	.034/ .037	.033/ .032		.033/ .026	.034	.033/ .029		.033/ .037
Al STD		.17	.17	.18/.17	.17	.18	.17		.18	.18	.18/.17		.18

NOTE: 1) All measurements with $BaSO_4$ calibration, measured in vacuum.
2) Values obtained at start/finish of sample measurement process.
3) After the 60 esh UV exposure, chamber pressure was at a max of 10⁷ Pa for less than 20 minutes.
4) Only 1B, 34, RPZ and PR10 were subjected to UV exposure in this period. Specimens 70, 71, 2B and 33 were parked in vacuum chamber.
5) All specimens were subjected to additional 577 esh of UV exposure in this period.

TABLE Z RESULTS OF PRELIMINARY STUDY OF COATING ADHESION TO GRAPHITE/EPOXY, KAPTON AND ALUMINUM SUBSTRATES

COATING	SUBSTRATE	THICKNESS (microns)	ADHESION BEFORE THERMAL CYCLING	ADHESION AFTER THERMAL CYCLING	ABSORPTANCE BEFORE THERMAL CYCLING	ABSORPTANCE AFTER THERMAL CYCLING	EMITTANCE BEFORE THERMAL CYCLING	EMITTANCE AFTER THERMAL CYCLING
PCBZ	GRAPHITE/ EPOXY	PS PRIMER (20) BASE COAT (50) TOP COAT (40)	4B/5B	4B	0.20	0.22	0.867	0.873
NS43G	GRAPHITE/ EPOXY	(122)	5B	0B	0.304	0.304	0.901	0.901
NS43G	KAPTON	(120)	06	OPTICAL PROPERTIES NOT MEASURABLE ON SAMPLE				
NS43G	ALUMINUM	(120)	5B	5B	0.308	0.308	0.895	0.895
HINCOM	GRAPHITE/ EPOXY	(125)	3B/4B	06	0.145	0.147	0.918	0.916
HINCOM	KAPTON	(105)	0B		0.138		0.918	
HINCOM	ALUMINUM	(105)	s6		0.132		8160	

Adhesion tests performed using ASTM D3359 Method B.

Thermal cycling consisted of 27 cycles between -180.0 and +180 °C.

For graphite/epoxy and KAPTON substrates were sprayed with a solution of 1% by weight Z-6040 in anydrous methanol prior to the application of HINCOM or NS43G.

Optical property and adhesion data for PCBZ, HINCOM, and NS43G represent the average of three determinations.

TABLE 'Ⅎ" ADHESION OF HINCOM AND HINCOM/NS43G COATINGS TO GRAPHITE/ ƐPOXⱯ AND KAPTON COATED COMPOS ITE SUBSTRATES

COATING	SUBSTRATE	SURFACE TREATMENT	ADHESION BEFORE THERMAL CYCLING	ADHESION AFTER THERMAL CYCLING[1] 4 CYCLES	ADHESION AFTER THERMAL CYCLING[1] 27 CYCLES	ADHESION AFTER THERMAL SHOCK[2]
HINCOM	GR/EP	RUB PRIME WNH HINCOM/Z-6040[3]	4B/5B	3B	0B/1B	3B
HINCOM	GR/EP	RUB PRIME WITH HINCOM/A-1100[4]	09			
HINCOM	KAPTON	RUB PRIME WNH HINCOM/Z-6040[3]	S6	5B	3B/4B	S8
HINCOM	KAPTON	RUB PRIME WITH HINCOM/A-1100[4]	S6	5B	sə	5B
HINCOM/ NS43G	GR/EP	RUB PRIME WITH HINCOM/NS43G/ Z-6040 MIXTURE[5]	se	5B	sə	sə
HINCOM/ NS43G	Ɛ Ɛ p	RUB PRIME WITH HINCOM/NS43G A-1100 MIXTURE[6]	00			
HINCOM	KEVLAR/ EPOXY	RUB PRIME WITH HINCOM/NS43G Ʌ-I 100 MIXTURE[6]	sə 5B	S0	se	S8

1„ THERMAL CYCLING CONSISTED OF Ʌ TOTAL OF 27 CYCLES FROM -180 °C TO +180 °C WITH Ʌ TEMPERATURE PROGAMMING MN-EOƐZHϽ4MƎIM„

Z„ THERMAL SHOCK CONSISTED OF 10 CYCLES FROM,ㄥ90 °C TO -70 °C AT Ʌ TEMPERATURE PROGRAMMING RATE 0ᔭ10qϽMINlſƐ„

3. 1 PART BY WEIGHT Z-6040 WITH 6 PARTS BY WEIGHT OF HINCOM PAINT.

4. ˥ PART BY WEIGHT A-1100 WITH 6 PARTS BY WEIGHT OF HINCOM PAINT.

S„ 1 PART BY WEIGHT Z-6040 WITH 6 PARTS BY WƐ16HT0ƐHINOOWNSɅƎOPMNI„

6„ 1 PART BY WEIGHT A-1100 WITH 6 PARTS BY WEIGHT OF HINCOM/NS43G PAINT.

TABLE 4. EFFECTS OF REFIRING AND PIGMENT-TO-BINDER RATIO ON THE ELECTRICAL CONDUCTIVITY OF HINCOM COATINGS

FORMULATION	ABSORPTANCE	EMITTANCE	CHARGING POTENTIAL (Volts at 10 keV, 0.5 nA/cm^2)
3:1 pigment-to-binder ratio non-refired pigment	0.15	0.91	-109
5.5:1 pigment-to-binder ratio pigment refired at 1050 “C for 15 minutes	0.18	0.91	-74
3:1 pigment to binder ratio pigment refired at 1050 °C for 15 minutes.	0.19	0.91	-32

TABLE 5 EFFECT OF TOPCOAT THICKNESS ON THE ELECTRICAL CONDUCTIVITY AND OPTICAL PROPERTIES OF PCBZ

TOPCOAT THICKNESS (microns)	CHARGING POTENTIAL (Volts at 10 keV, 0.5 nA/cm^2)	ABSORPTANCE	EMITTANCE
125	+16	0.15	0.90
63	+12	0.19	0.89
40	-t-lo	0.20	0.86

Note. The samples with 125 micron and 63 micron thick topcoats were prepared on aluminum substrates. The sample with the 40 micron thick topcoat was prepared on a graphite epoxy substrate.

TABLE 6 SUMMARY OF WHITE PAINT DATA AND ESTIMATED END OF LIFE PROPERTIES

PAINT SYSTEM	ABSORPTANCE BOL	ABSORPTANCE DELTA ABS	ABSORPTANCE UNCERTAINTY	ABSORPTANCE EOL	EMITTANCE	ABS/EMITT (EOL)	ADHESION (SEE NOTE 5) ALUMINUM	ADHESION GR/EP	ADHESION KAPTON	ESD (VOLTS)	USE
HINCOM	0.15	0.05 (SEE NOTE 1)	0.05	0.25	0.91	0.27	5B	1B	5B	-120	FSS RF METAL PARTS
NS43G	0.31	0.05 (SEE NOTE 2)	0.05	0.41	0.90	0.45	5B	0B	NOT APPLICABLE	-4	BACK OF MAIN REFLECTOR
NS43G/HINCOM	0.20	0.05 (SEE NOTE 3)	0.05	0.30	0.91	0.33	5B	5B	NOT APPLICABLE	-10	CFRP/KFRP PARTS METAL PARTS
PCBZ PS-PRIMER (20 MICRONS) PCBZ BASECOAT (50 MICRONS) PCBZ TOPCOAT (40 MICRONS)	0.20	0.15 (SEE NOTE 4)	0.05	0.40	0.86	0.46	5B	4B	NOT APPLICABLE	10	BACK AND FRONT OF MAIN REFLECTOR

NOTE 1 NO ABSORPTANCE INCREASE AFTER 2500 ESH UV
ABSORPTANCE INCREASE OF 0.04 AFTER ELECTRON AND PROTON EXPOSURE

NOTE 2 NO ABSORPTANCE INCREASE AFTER 2500 ESH UV
ABSORPTANCE INCREASE OF 0.03 AFTER ELECTRON AND PROTON EXPOSURE

NOTE 3 DELTA ABS IS BASED ON THE ARITHMETIC MEAN OF EXPERIMENTAL DEGRADATION RESULTS
OBTAINED FOR NS43G AND HINCOM COATINGS AND "EDUCATED GUESS"

NOTE 4 ABSORPTANCE INCREASE OF 0.03 AFTER 2500 ESH UV
ABSORPTANCE INCREASE OF 0.07 AFTER ELECTRON AND PROTON EXPOSURE

NOTE 5 ADHESION RATING WAS TAKEN AS THE LOWER OF THE ADHESION RATINGS OBTAINED BY PERFORMING ASTM D3359 METHOD B ADHESION TESTS AFTER THERMAL CYCLING AND AFTER THERMAL SHOCK TESTS PERFORMED ON SAMPLES PREPARED USING THE MOST EFFECTIVE SAMPLE PRETREATMENT PROCEDURES

GENERAL NOTE SPECULARITY MEASUREMENTS PERFORMED ON HINCOM, HINCOM/NS43G, AND PCBZ COATINGS SHOWED VERY LOW SPECULARITY, INDICATING THAT SPECULARITY WOULD NOT BE A SIGNIFICANT PROBLEM FOR THESE COATINGS OR FOR HINCOM/NS43G.

CONCERNS THE EFFECTS OF HIGH ENERGY PARTICLE RADIATION NEED FURTHER INVESTIGATION

ASUMPTIONS DELTA ABS IS BASED ON IN-SITU MEASUREMENTS AND "EDUCATED GUESS"
UNCERTAINTY ADDED TO ACCOUNT FOR EFFECTS NOT YET FULLY EVALUATED, SUCH AS EFFECTS OF HIGH ENERGY PARTICLE RADIATION